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(54) **METHODS AND APPARATUSES FOR ELECTRONIC TIME DELAY AND SYSTEMS INCLUDING SAME**

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E21B 43/1185 (2006.01)

(52) **U.S. Cl.** **166/55.1**; 175/4.54

(58) **Field of Classification Search** 166/297, 166/55.1; 175/4.54

See application file for complete search history.

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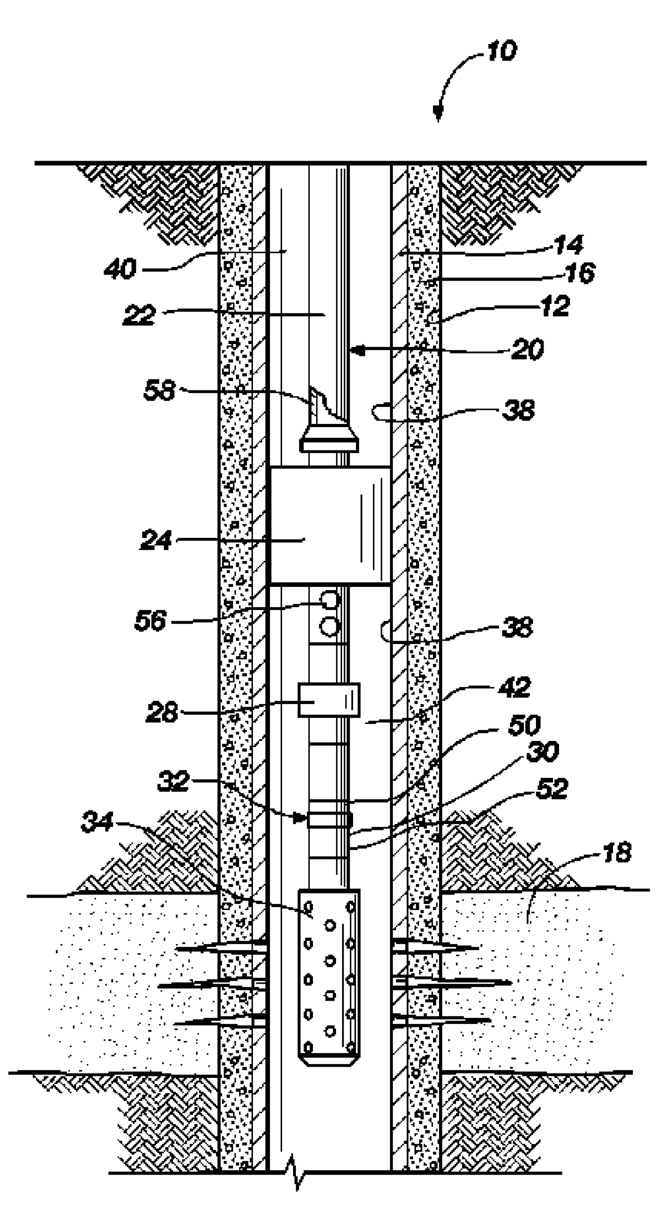
(57) **ABSTRACT**

Electronic time delay apparatuses and methods of use are disclosed. An explosive or propellant system, which may be configured as a well perforating system includes an electronic time delay assembly comprising an input subassembly, an electronic time delay circuit, and an output subassembly. The input subassembly is activated by an external stimulus, wherein an element is displaced to activate an electronic time delay circuit. The electronic time delay circuit comprises a time delay device coupled with a voltage firing circuit. The electronic time delay circuit counts a time delay, and, upon completion, raises a voltage until a threshold firing voltage is exceeded. Upon exceeding the threshold firing voltage, a voltage trigger switch will break down to transfer energy to an electric initiator to initiate an explosive booster within the output subassembly. The explosive booster provides a detonation output to initiate the next element explosive or propellant element, such as an array of shaped charges in the well perforating system.

35 Claims, 6 Drawing Sheets



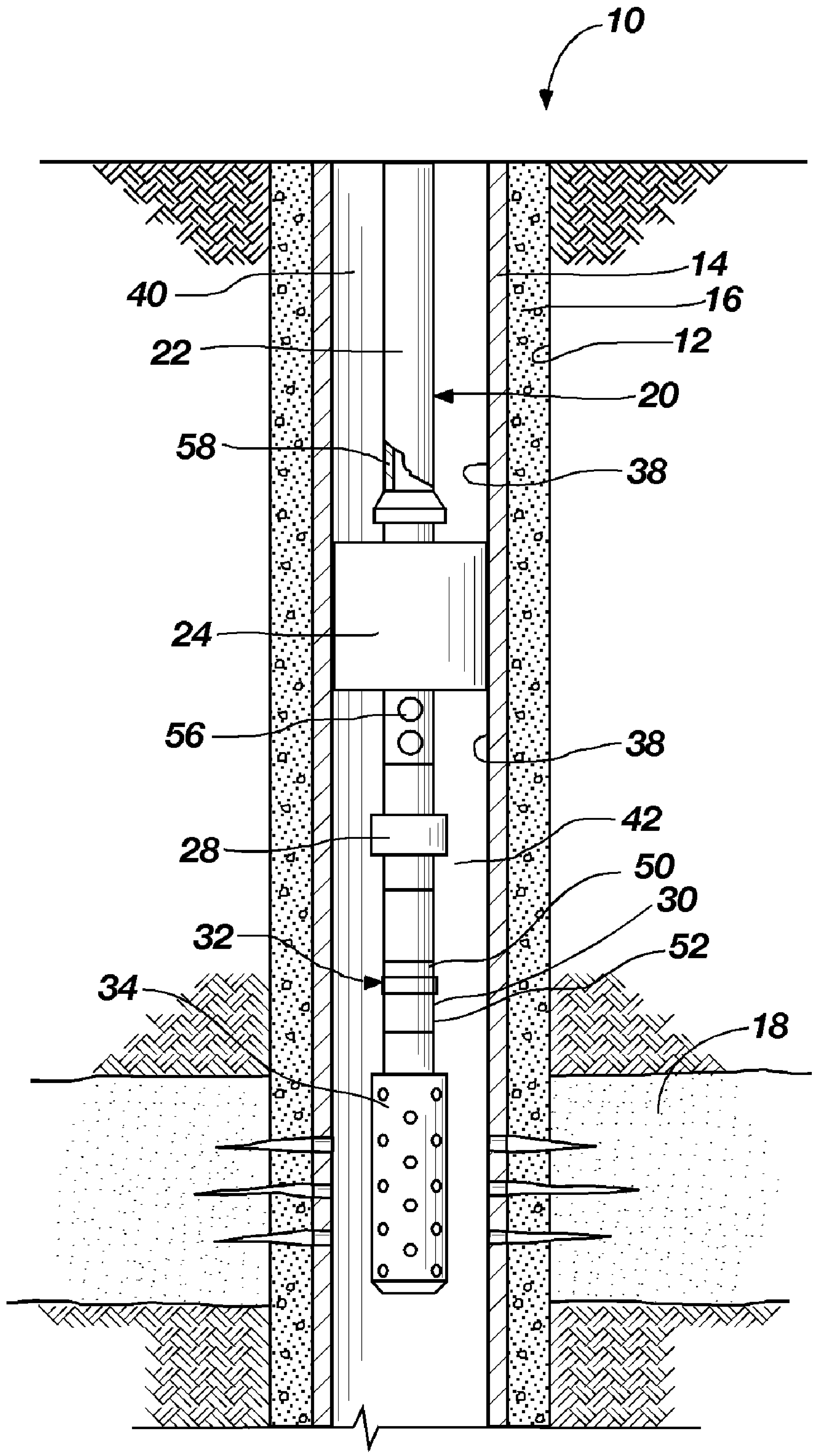


FIG. 1

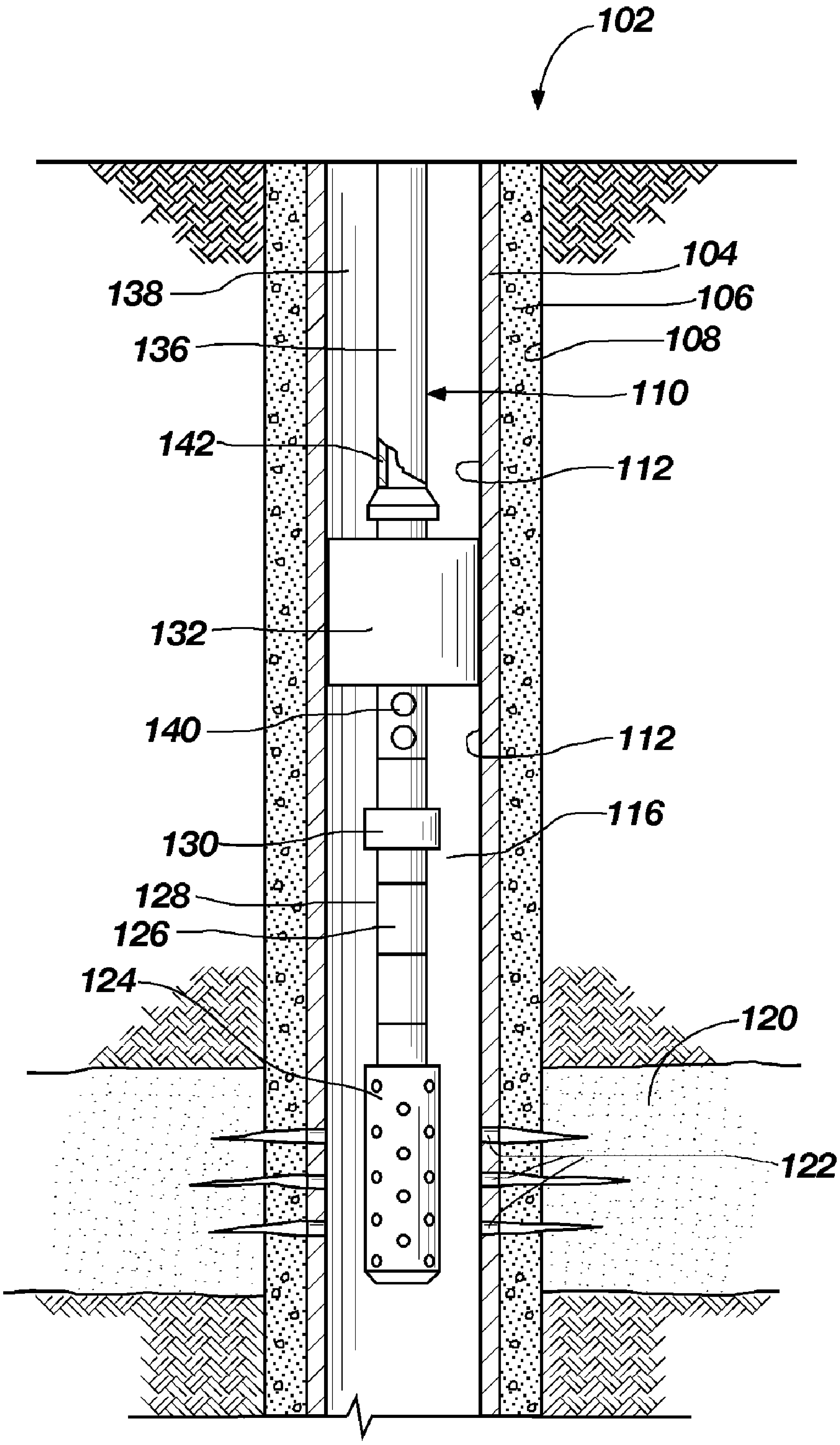

102
104
106
108
110
112
112
116
120
122
138
136
142
132
140
130
128
126
124

FIG. 2

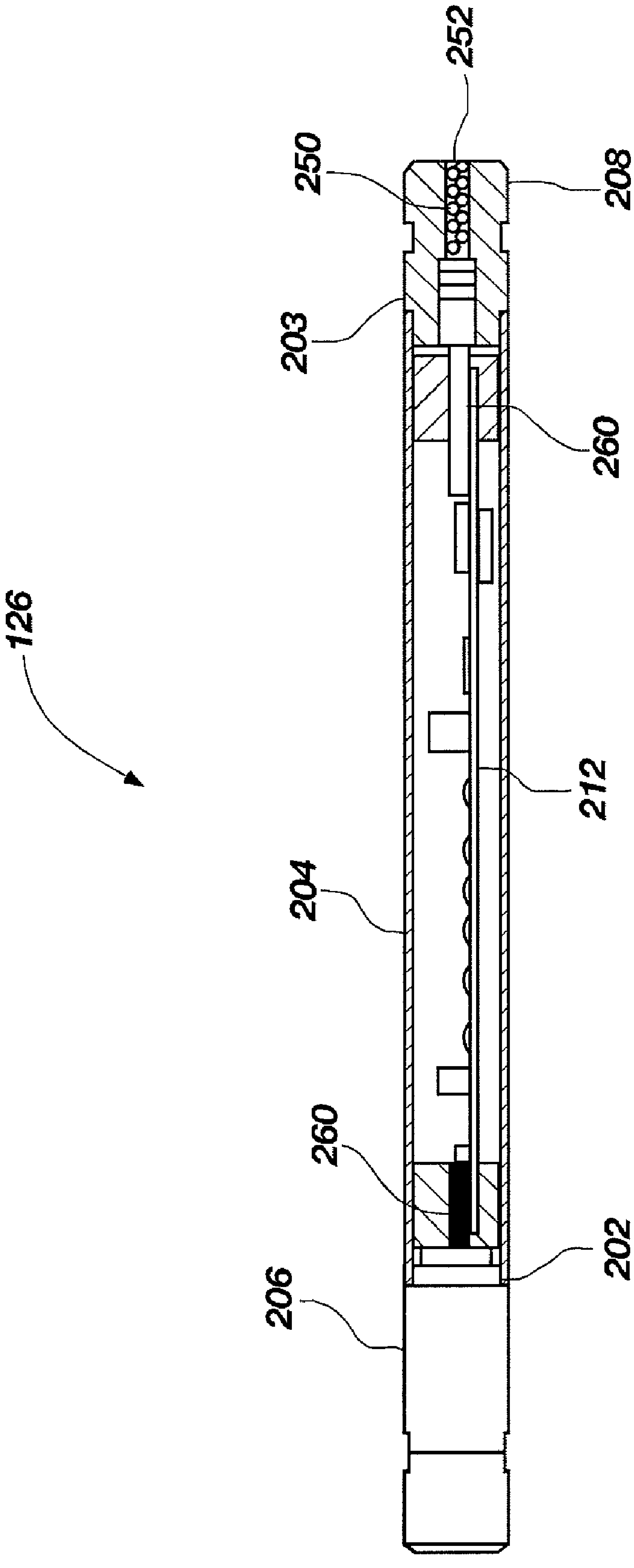
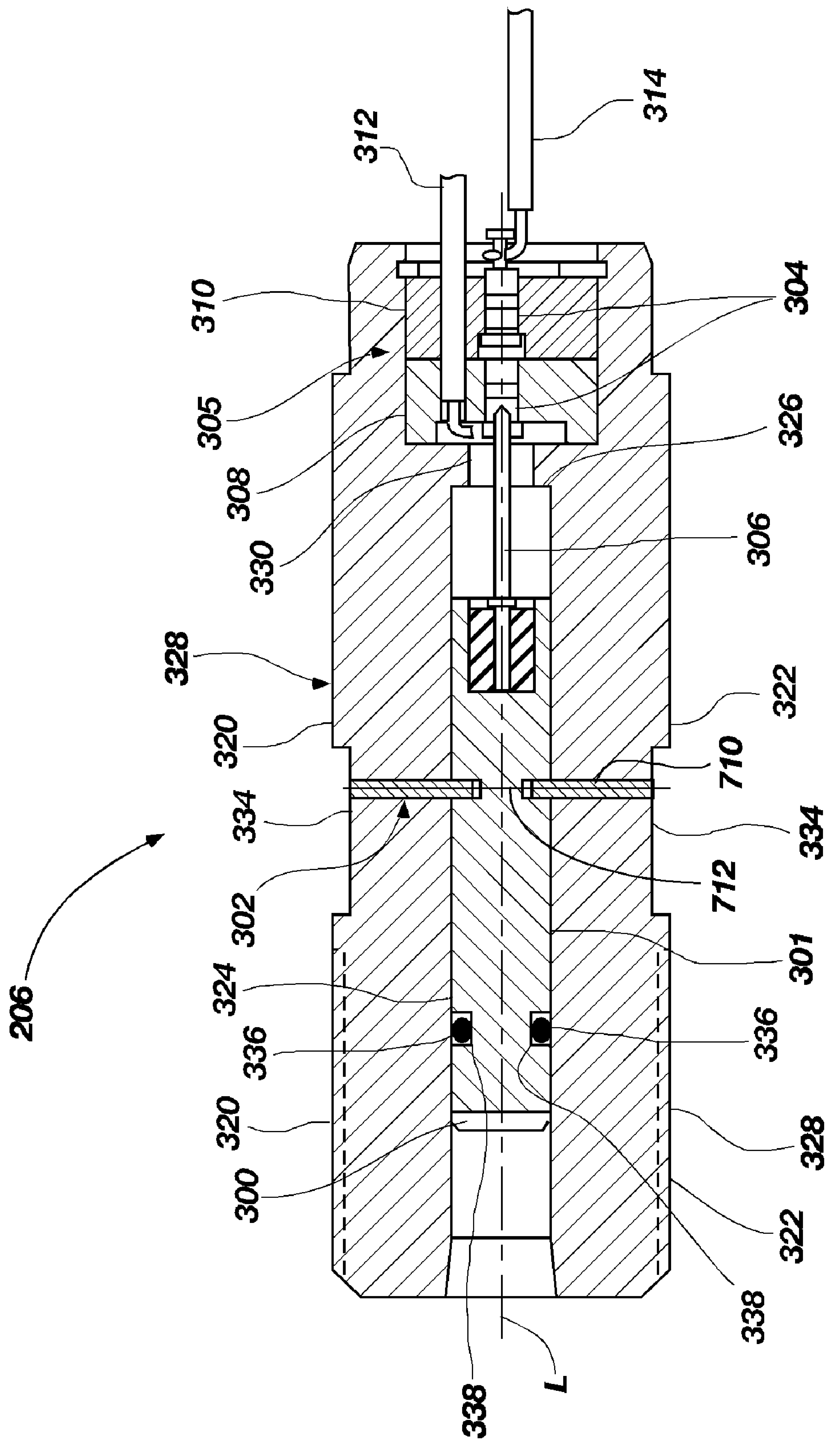


FIG. 3



206
312
314
310
304
305
308
326
330
306
328
320
322
710
334
334
712
302
301
324
336
336
320
328
300
322
338
338
L

FIG. 4

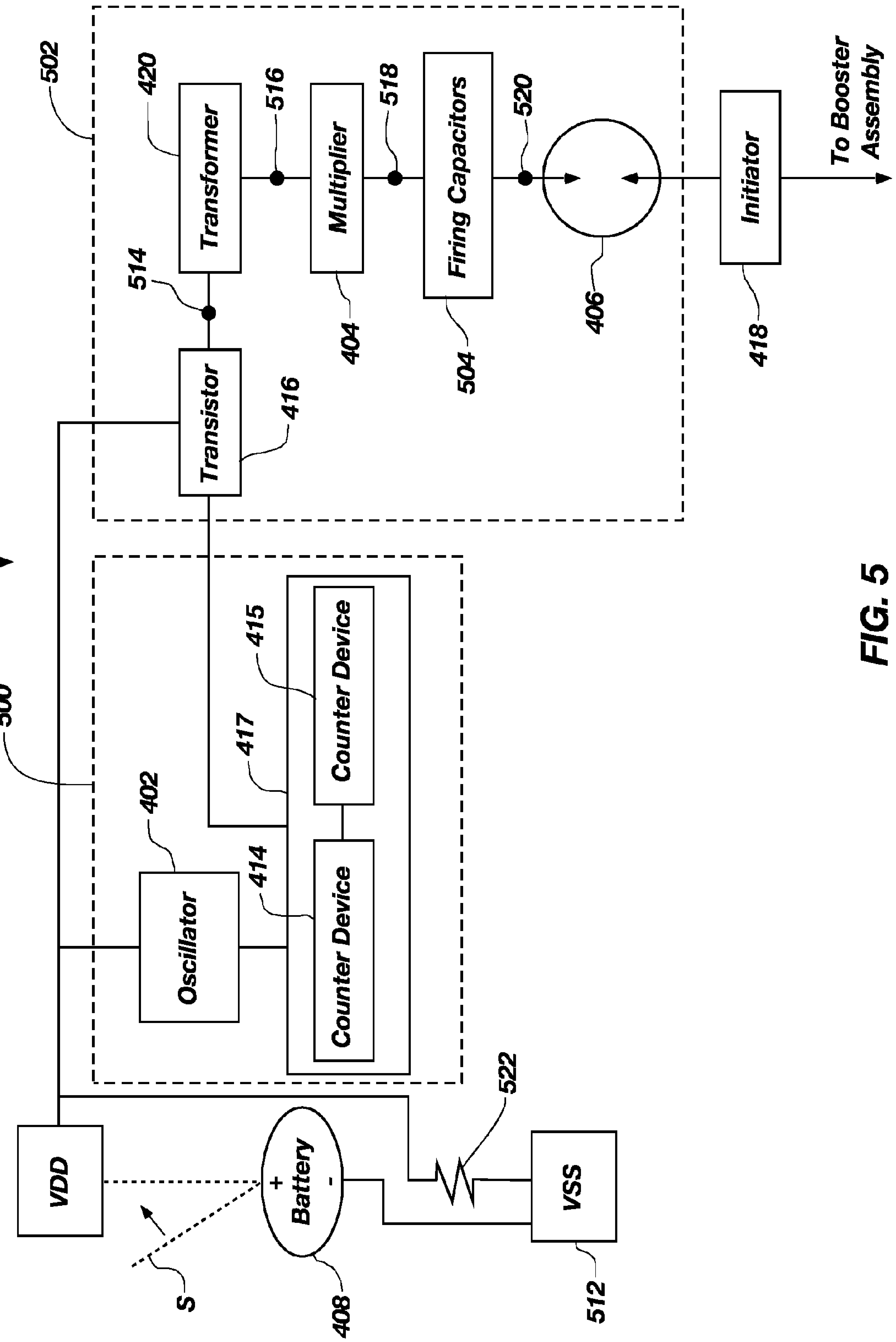

212
500
502
Transformer
420
516
Multiplier
518
Firing Capacitors
520
514
Transistor
416
404
504
406
Initiator
418
To Booster Assembly
Oscillator
402
Counter Device
414
Counter Device
415
417
VDD
Battery
+
-
408
S
522
VSS
512

FIG. 5

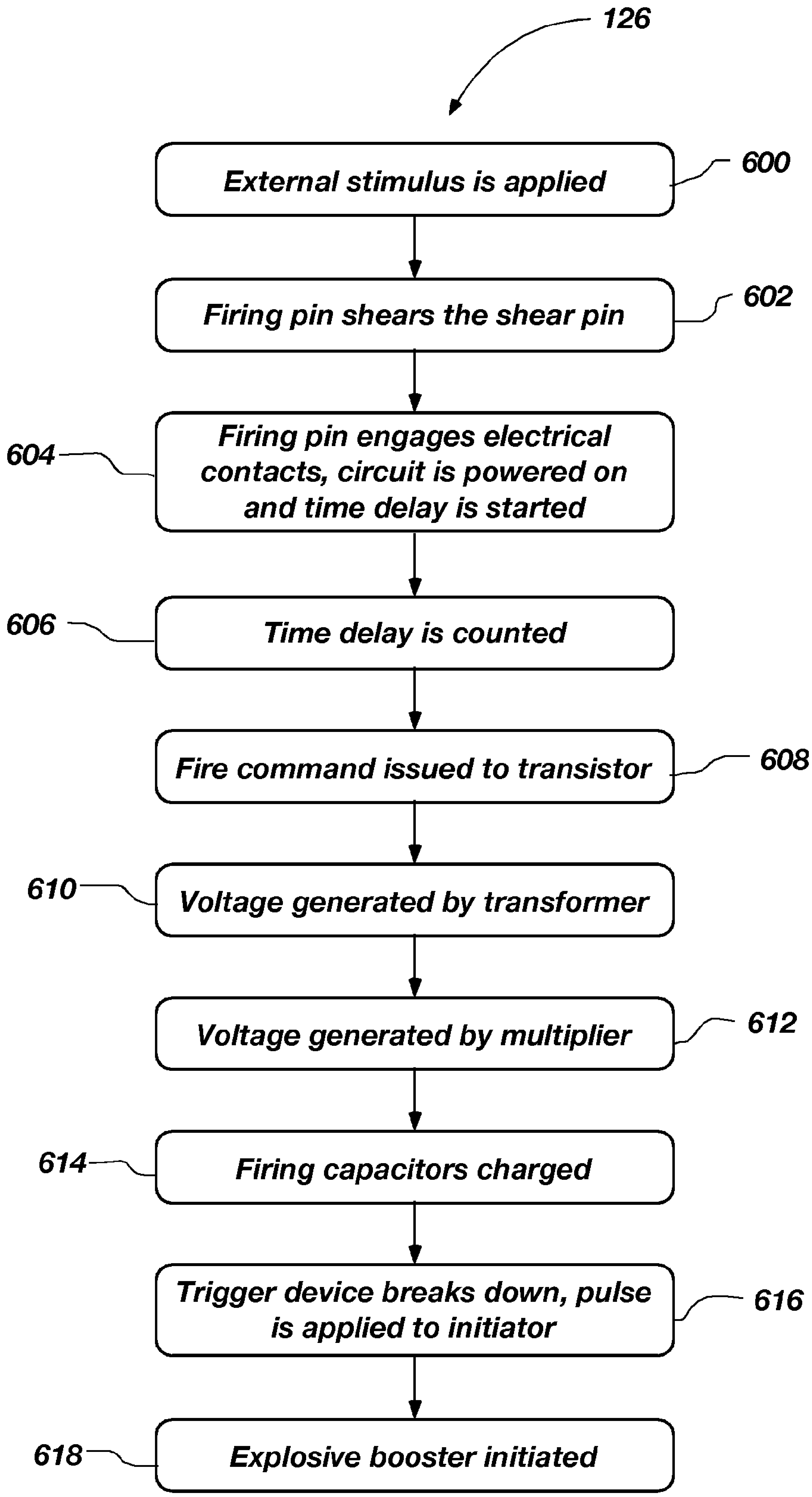

126
External stimulus is applied
600
Firing pin shears the shear pin
602
Firing pin engages electrical contacts, circuit is powered on and time delay is started
604
Time delay is counted
606
Fire command issued to transistor
608
Voltage generated by transformer
610
Voltage generated by multiplier
612
Firing capacitors charged
614
Trigger device breaks down, pulse is applied to initiator
616
Explosive booster initiated
618

FIG. 6

METHODS AND APPARATUSES FOR ELECTRONIC TIME DELAY AND SYSTEMS INCLUDING SAME

CROSS-REFERENCE TO RELATED APPLICATION

This application is also related to U.S. patent application Ser. No. 11/876,841, filed Oct. 23, 2007, now U.S. Pat. No. 7,789,153, issued Sep. 7, 2010 for METHODS AND APPARATUSES FOR ELECTRONIC TIME DELAY AND SYSTEMS INCLUDING SAME.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention, in various embodiments, relates generally to time delay apparatuses and, more specifically, to apparatuses comprising an electronic time delay assembly suitable for use in initiating explosives and propellants, as well as systems including an electronic time delay system and methods of operation thereof.

2. State of the Art

Perforating systems used for completing an oil or gas well are well known in the art. Well bores, which are drilled through earth formations for extracting hydrocarbons in the form of oil and gas, are conventionally lined by inserting a steel casing or liner into the well, and cementing at least a portion of the casing or liner in place to prevent migration of high pressure fluids up the well bore outside the casing or liner. The subterranean formation or formations having the potential to produce hydrocarbons are directly linked with the interior of the casing or liner by making holes, referred to as perforations, through the wall thereof, through surrounding cement and into the formation. Perforations are conventionally made by detonating explosive shaped charges disposed inside the casing at a location adjacent to the formation which is to produce the oil or gas. The shaped charges are configured to direct the energy of an explosive detonation in a focused, narrow pattern, called a "jet," to create the holes in the casing.

Conventionally, well perforation systems include a firing head and a perforating gun, both of which are suspended from, and lowered into, a well on a conveyance device such as a tubular string, which may comprise so-called "coiled tubing." Well perforation systems also conventionally comprise various components including, for example, a packer, a firing pin, an explosive booster, and a time delay device. A time delay device is needed to provide an operator sufficient time between a pressurizing event and a subsequent perforation event in order to pressure balance a well for perforation to secure optimal flow of oil or gas flow into the well. Pressure balancing a well is an important procedure because failure to do so, or if the procedure is done incorrectly, may lead to equipment damage as well as possible injury to equipment operators if insufficient hydrostatic pressure is present in the casing or liner or, if too great a hydrostatic pressure is present, the producing formation exposed by the perforating operation may be contaminated or production compromised or prevented without remedial measures. Additionally, with a properly pressure-balanced well, producing formation fluid will immediately and rapidly flow upward through the interior of the tubular string and toward the earth's surface in an appropriate, controlled manner. Therefore, it is important that the timing delay device employed be reliable and accurate in order to allow for adequate time to pressure balance a well. Time delay devices currently used in the art employ pyrotechnic time delay fuses. As described below in greater detail, pyrotechnic fuse-based time delay devices have reliability and accuracy concerns, as well as time limitations which may eventually lead to greater complexity and increased costs for customers of the oil tool industry.

FIG. **1** illustrates a conventional well perforating system **20** within well **10**. The well **10** is constructed by first drilling a well bore **12**, within which a well casing **14** is placed and cemented in place as indicated at **16**. The perforating gun **34**, mechanical release **28**, packer **24**, and firing head **32** are, among other components, carried by tubular string **22**. The perforating gun **34** and firing head **32** are lowered on the tubular string **22** to a selected location in the well **10** adjacent to the subsurface formation **18**, which is to be produced. A seal is provided by packer **24** between the exterior of tubular string **22** and wall **38** of casing **14** to define a well annulus **40** above packer **24** and an isolated zone **42** below packer **24**. Perforating system **20** also includes a vent **56** located below packer **24**. Vent **56** allows for a direct link between the isolated zone **42** and tubing bore **58** to ensure fluid pressure within tubing bore **58** and isolated zone **42** are substantially equal. At the time designated to fire the perforating gun **34**, an actuating piston **50** within firing head **32**, is moved in response to an increase in fluid pressure in tubular string **22** initiated by the operator. The movement of the piston **50** releases a firing pin **52**, thus initiating a firing sequence.

As mentioned above, conventional perforating systems may provide for a pyrotechnic time delay device **30** located within firing head **28**. The pyrotechnic time delay device **30** provides for a time delay between the initiation of the firing head **28** and the subsequent firing of the shaped charges carried by the perforating gun **34** in order to, as described above, pressure balance the well **10** for optimal perforation. Pyrotechnic time delay devices as known in the art provide a maximum time delay of eight minutes. Therefore, in order to achieve longer delays, an operator is forced to string multiple pyrotechnic time delay devices together in a series formation. For example, additional delays may be coupled together so as to achieve a longer delay timer.

Due to the time and expense involved in perforating well bores and the explosive power of the devices used, it is essential that their operation be reliable and precise. Stringing together multiple pyrotechnic time delay devices diminishes the system's reliability and increases the system cost and complexity.

There is a need for methods and apparatuses to provide increased system reliability and flexibility of operation of well perforating systems. Specifically, there is a need for a time delay device used in a well perforating system to allow for adequate and precise timing of operation of a well perforating system in order to pressure balance a well for optimal perforation results. Such a time delay device would desirably exhibit a high level of reliability at a low level of cost and complexity of fabrication.

BRIEF SUMMARY OF THE INVENTION

An embodiment of the present invention comprises a time delay apparatus comprising an input assembly including an element positioned to be displaced to enable a power source connection. The time delay apparatus further includes an electronic time delay circuit operably coupled to the input assembly and configured to provide a time delay responsive to the enabled power source connection and initiate a fire command upon completion of the time delay.

Another embodiment of the present invention includes a well perforation system including a conveyance device, a perforating gun suspended from the conveyance device, a firing head suspended from the conveyance device and operably coupled to the perforating gun, and a time delay apparatus within the firing head. The time delay apparatus includes an input assembly including an element positioned to be displaced to enable a power source connection, an electronic time delay circuit operably coupled to the input assembly and configured to provide a time delay responsive to an enabled power connection and initiate a fire command upon completion of the time delay.

Yet another embodiment of the present invention includes a method of using an electronic time delay apparatus within an explosive or propellant system. The method comprises applying an external force to an element to displace the element responsive to the external force, connecting a power source to an electronic time delay circuit responsive to the displacement of the element, providing an electronic time delay responsive to connection of the power source; and increasing a voltage from the power source to a predetermined, higher threshold firing voltage after the electronic time delay.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. **1** is a cross-sectional illustration of a conventional perforating system within a well;

FIG. **2** is a cross-sectional illustration of an explosive or propellant system configured as a well perforating system in accordance with an embodiment of the invention;

FIG. **3** is a cross-sectional illustration of an electronic time delay assembly in accordance with an embodiment of the invention;

FIG. **4** is a cross-sectional illustration of a firing pin subassembly in accordance with an embodiment of the invention;

FIG. **5** is a block diagram of an electronic time delay circuit in accordance with an embodiment of the invention; and

FIG. **6** is a flow diagram of an electronic time delay assembly according to an embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention, in various embodiments, comprises apparatuses and methods of operation for an electronic time delay assembly suitable for use within an explosive or propellant system configured, by way of nonlimiting example, as a well perforating system to address the reliability concerns, as well as the cost and complexity issues associated with conventional time delay devices.

In the following description, circuits and functions may be shown in block diagram form in order not to obscure the present invention in unnecessary detail. Conversely, specific circuit implementations shown and described are examples only and should not be construed as the only way to implement the present invention unless specified otherwise herein. Additionally, block definitions and partitioning of logic between various blocks is exemplary of a specific implementation. It will be readily apparent to one of ordinary skill in the art that the present invention may be practiced by numerous other partitioning solutions. For the most part, details concerning timing considerations, and the like, have been omitted where such details are not necessary to obtain a complete understanding of the present invention and are within the abilities of persons of ordinary skill in the relevant art.

In this description, some drawings may illustrate signals as a single signal for clarity of presentation and description. It will be understood by a person of ordinary skill in the art that the signal may represent a bus of signals, wherein the bus may have a variety of bit widths and the present invention may be implemented on any number of data signals including a single data signal.

In describing embodiments of the present invention, the systems and elements incorporating embodiments of the invention are described to facilitate an enhanced understanding of the function of the described embodiments of the invention as it may be implemented within these systems and elements.

FIG. **2** illustrates an embodiment of an explosive or propellant system configured as a well perforation system **110** disposed within a well **102**. The well **102** is constructed by first drilling a well bore **108** within which is placed a well casing **104**, which is cemented in place as indicated at **106**. The well **102** intersects a subsurface formation **120** from which it is desired to produce hydrocarbons such as oil and/or gas. The system **110** includes a conveyance device **136** coaxially inserted inside the casing **104**. Conveyance device **136** may be any suitable device, such as a wireline, slickline, tubing string, coiled tubing, and the like. As depicted, conveyance device **136** comprises a tubular string and, for brevity and ease of description, will be referred to herein as a tubing string. The tubing string **136** extends from a drilling rig on the surface through casing **104** and components of a well perforating system, such as packer **132**, mechanical release **130**, firing head **128**, and perforating gun **124**, are disposed at the lower, or distal, end thereof.

The packer **132** provides a structure for sealing between the exterior of tubing string **136** and a wall **112** of casing **104** that may also be referred to as a casing bore wall or well bore wall **112**. The resulting seal provides a well annulus **138** between the tubing string **136** and well bore wall **112** above the packer **132** and an isolated zone **116** of well **102** below packer **132**. Perforating system **110** also includes a vent **140** located below the packer. Vent **140** allows for hydraulic communication between isolated zone **116** and tubing bore **142** to ensure fluid pressures within the tubing bore **142** and isolated zone **116** are substantially equal.

The perforating gun **124** is suspended from the tubing string **136** in the isolated zone **116** adjacent to the subsurface formation **120**, which is to be perforated. The perforating gun **124** is configured to detonate and fire shaped charges to create holes, or perforations **122**, in casing **104** and into the surrounding cement **106** and formation **120**. FIG. **2** illustrates a well perforating system at a time subsequent to the detonation of perforation gun **124**; therefore casing **104**, cement **106** and formation **120** include perforations **122** extending therethrough. When the tubing string **136** and the components of well perforating system **110** are first lowered into the well **102**, the perforations **122** illustrated in FIG. **2** will not be present. The mechanical release **130** enables an operator to drop the perforating gun **124** to the bottom of well **102** after the perforating gun **124** has been fired.

Also suspended from the tubing string **136** and located above the perforating gun **124** is the firing head **128**. Firing head **128** includes, among other components, an electronic time delay assembly **126** according to an embodiment of the invention. As described in detail below, electronic time delay assembly **126** provides multiple safety features including various circuit and trigger isolation features as well as mechanical isolation features. Additionally, the electronic delay assembly **126** provides a time delay so as to allow an operator sufficient time to pressure balance well **102** for optimal perforation. Stated another way, the time delay allows time for an operator to alter the pressure in isolated zone **116** to the requirements of the formation fluids in formation **120**. Electronic time delay assembly **126** provides this delay time capability by enabling longer, and more highly selectable, time delays in comparison to conventional pyrotechnic time delay uses. By way of example only, electronic time delay assembly **126** may provide a selected time delay duration of up to, for example, at least ten hours.

FIG. **3** illustrates an electronic time delay assembly **126** according to an embodiment of the present invention. As described and illustrated in detail below, the electronic time delay assembly **126** provides significantly improved functions in a well perforating system including providing a reliable and increased time delay, increasing the duration of time delay, and providing safety features including circuit and explosive booster initiator isolation.

As illustrated in FIG. **3**, electronic time delay assembly **126** may include an input module **206**, an electronic time delay circuit **212**, and an output module **208**. Input module **206** may be configured as a firing pin subassembly, while output module **208** may be configured as an explosive booster subassembly. Electronic time delay circuit **212** is contained in a central, tubular housing **204** that may be attached, as by laser welding to input module **206** and output module **208** at locations **202** and **203**, respectively. For example only, the tubular housing **204** may be made of steel with resilient retainers **260** at each end of the tubular housing **204**. The resilient retainers **260** provide mechanical support as well as electrical and mechanical isolation of the electronic time delay circuit **212**. Output module **208**, which will be described in greater detail below, may be configured to provide a detonation output to trigger the subsequent firing of perforating gun **124** (see FIG. **2**).

FIG. **4** illustrates input module **206** according to an embodiment of the present invention. Input module **206**, as illustrated, comprises firing pin **301**, a shear pin assembly **302**, and a contact assembly **305** carried by housing **328** having a firing pin bore **324** therethough, firing pin bore **324** necking down to a smaller intermediate diameter bore at **330** and then increasing in diameter at contact assembly **305**. Shear pin assembly **302** may include a single shear pin **712** extending transversely across housing **328** or may comprise a double shear pin configuration comprising a first shear pin **712** and a second shear pin **710**, each extending into firing pin **301**. Shear pin assembly **302** extends from a first side **320** to a second side **322** of input module **206** through firing pin **301** and apertures **334** in the wall of housing **328**. By way of example, shear pin assembly **302** may comprise a coiled spring pin. Contact assembly **305** may include a first contact assembly **308**, a second contact assembly **310**, and annular contact **304** extending through both the first and second contact assemblies **308** and **310**, respectively. Lead wires **312** and **314** may protrude from one end of firing pin subassembly **206** and may be operably coupled to electronic time delay circuit **212** (see FIG. **3**). Lead wire **312** is connected to an annular contact **304** carried by first contact assembly **308**, while lead wire **314** is connected to an annular contact **304** carried by second contact assembly **310**.

Firing pin **301**, which is disposed in firing pin bore **324**, has a longitudinal axis L and may include a pin contact **306** located extending from at one end of firing pin **301**. The opposite end **300** of firing pin **301** is configured to receive a firing stimulus from an external force, such as, for example only, hydraulic pressure in isolated zone **116** (see FIG. **2**) or an impact force from a dropped weight. As shown, firing pin **301** is configured for pressure actuation and includes an annular seal **336** disposed thereabout in annular groove **338**. Sufficient external force acting on firing pin **301**, and specifically on end **300**, shears pins **710**, **712** of shear pin assembly **302** and allows the firing pin **301** to be displaced to the right (as the drawing is oriented), or downwardly within well perforating system **110** (see FIG. **2**) and toward contact assembly **305**. Upon displacement, the firing pin **301** may then travel a fixed distance down the firing pin subassembly **206**, stopping at annular wall **326** which may then enable pin contact **306** to extend further into contact assembly **305**. Upon entering contact assembly **305**, pin contact **306** engages both electrical contacts **304** and acts as a switch S to connect a power source **408**, which may also be referred to as battery **408**, to the electronic time delay circuit **212** (see FIG. **5**). For brevity and ease of description, power source **408** will be referred to herein as a battery **408**. Upon connection of the battery **408**, electronic time delay circuit **212** will power up, and the desired, selected time delay will begin. Power source **408** may also comprise a capacitor-type power storage device instead of a battery, or power may be provided from an external power source. The type of power source **408** employed is not significant to the practice of the present invention, and an optimum type of power source may vary with the specific embodiment and application of the invention.

As described above, input module **206** acts as an electrical switch that requires an external force or stimulus in order to be activated. This configuration provides for a significant safety feature by isolating the battery **408** from the electronic time delay circuit **212** (FIG. **5**) until a satisfactory external force or stimulus is applied. Therefore, any chance of premature detonation is substantially eliminated. The type and magnitude of the required external force or stimulus may vary according to the embodiment and application of the present invention, and is not limited to applied pressure or impact force as discussed above.

FIG. **5** illustrates a block diagram of electronic time delay circuit **212** according to an embodiment of the present invention. As described below, time delay circuit **212** comprises an electronic time delay device **500** coupled with a voltage firing circuit **502**. Time delay circuit **212** also comprises a battery **408** and supply voltage terminal VDD. As described above in reference to FIG. **4**, battery **408** is selectively connectable to supply voltage terminal VDD by way of an electrical switch S provided by electrical contacts **304** in cooperation with pin contact **306**. When the pin contact **306** engages annular contact **304**, battery **408** is connected to supply voltage terminal VDD, thus connecting electronic time delay device **500** and voltage firing circuit **502** to battery **408**. By way of example only, battery **408** may supply a continuous current at an open circuit voltage of below ten volts, one suitable voltage being about 3.90 volts (VDC).

Electronic time delay device **500** comprises an oscillator **402** which oscillates at a selected frequency and is operably coupled with counter device **417**. Oscillator **402** and counter device **417** are configured to count a desired time delay. By way of example, and not limitation, oscillator **402** may comprise a 75 kHz crystal oscillator. Counter device **417** may comprise, by way of example only, a pair of CD4060B binary counter/divider devices **414**, **415**, offered by Texas Instruments of Dallas, Tex. Depending on the desired time delay, a single counter device may be used or multiple counter devices may be coupled together in series to achieve a longer delay. For example, if an eight-minute time delay is desired, a single eight-minute counter device may be used. Similarly, if a thirty-minute time delay is desired, a thirty-minute counter device may be use. On the other hand, if a thirty-minute counter device is unavailable, then a pair of counter devices, with a total delay time of thirty minutes may be coupled in series in an adder configuration to count the desired delay. For example only, one twenty-minute counter/divider device may be coupled with a ten-minute counter, or alternatively, two fifteen-minute counters may be coupled together to produce the desired thirty-minute delay. Alternatively, a pair of counter devices may be coupled in series in a multiplier configuration in order to achieve the desired time delay. For, example only, if a thirty-minute time delay is desired using a multiplier configuration, a first device would count up to fifteen minutes and upon completion of the fifteen minutes, a second device would increment to a value of one. Subsequently, the first device would again count up to fifteen minutes, and upon completion, the second device would increment to a value of two. Therefore, in a multiplier configuration example, with a 75 kHz oscillator, the first device is only required to count up to fifteen minutes and the second device is only required to count to a value of two.

As opposed to conventional pyrotechnic time delays, the embodiment of the invention may, for example only, provide time delays from a short duration such as eight minutes up to a much longer duration of, for example, a number of hours. This capability reduces cost and complexity and increases operational flexibility and reliability in comparison to conventional pyrotechnic fuse-type time delay devices because only one time delay unit and setting and only one detonation transfer event is required. Additionally, because of the high level of accuracy of electrical components, the timing accuracy and precision of an electronic time delay is improved over a conventional pyrotechnic time delay fuse, which may suffer from unpredictable burning rates.

As illustrated in FIG. **5**, electronic time delay device **500** is operably coupled to a high voltage generator transistor **416** that may act as a switch and is thereafter operably coupled to a transformer **420**. The transformer **420** is in turn operably coupled to a voltage multiplier **404**. For example, and not limitation, transformer **420** may be configured to generate a voltage of about 550 VAC from an input of about 3 VDC. Multiplier **404**, comprising a four stage diode/capacitor pair configuration, may be configured to generate a voltage of about 600 VDC from the 550 VAC input. Voltage multiplier **404** is operably coupled to firing capacitors **504**, which are then operably coupled to the input side of the trigger **406**. Firing capacitors comprise, for example, three 0.1 μF capacitors charged through a 22 Mohms resistor, firing capacitors **504** exhibiting a spark gap ignition voltage of substantially 600 V. The output side of the trigger **406** is operably coupled to an initiator **418** which is then operably coupled to the explosive booster subassembly **208** (see FIG. **3**). By way of example, and not limitation, trigger **406** may comprise a gas discharge tube that will not conduct unless (in the described embodiment) a voltage level of 600 V or above is applied across the tube. In some cases, it may be desirable for trigger **406**, or a gas discharge tube, to comprise a different breakdown voltage. Therefore, voltage multiplier **404**, as configured, may have the capability to generate a voltage of substantially 2500 V.

The operation of circuit **212** illustrated in FIG. **5** will now be described. After pin contact **306** within input module **206** engages both electrical contacts **304** (see FIG. **4**), battery **408** is connected to the circuit **212**, thus starting the desired, selected time delay. The desired, selected time delay is provided using oscillator **402** in conjunction with a counter device **417**. As described above, the time delay may be programmed or preselected by using one or more counter/divider devices **414**, **415** to produce the desired time delay. Upon completion of the desired, selected time delay, electronic time delay device **500** issues a fire command at the gate of the high voltage generator transistor **416**. Subsequently, the battery voltage at node **514** is input into transformer **420** and transformer **420** generates a first intermediate voltage at node **516** that is substantially higher than the battery voltage at node **514**. Thereafter, the first intermediate voltage at **516** is input into voltage multiplier **404** and voltage multiplier **404** generates a second intermediate voltage at node **518** that is substantially higher than that at the first intermediate voltage at node **516**. Firing capacitors **504** are then charged and, upon reaching a threshold firing voltage at node **520**, firing capacitors **504** apply a pulse to an initiator **418** through the trigger **406**. By way of example only, trigger **406** may have a breakdown voltage of 600 V. Therefore, as the voltage in firing capacitors **504** reaches 600 V, trigger **406** breaks down and the voltage is applied across trigger **406** and at initiator **418**, which then initiates an explosive booster contained in explosive booster subassembly **208** (see FIG. **3**).

Trigger **406** provides a significant safety feature of the embodiment of the invention by isolating the initiator **418** from the circuit **212** which, in turn, provides isolation and safety from electrostatic discharge (ESD) and stray voltage which could result in premature detonation. As a further safety feature the oscillator **402** of circuit **212** may be configured to continue oscillating after the time delay has passed and after a voltage is applied at initiator **418**. Therefore, any residual energy stored in battery **40S** will be drained by the charging and de-charging oscillator. Additionally, one embodiment of the invention may comprise a resistor **522** operably coupled between battery **408** and a ground voltage VSS. Therefore, any residual energy stored in battery **408** may be drained to ground voltage VSS through resistor **522**.

Whereas one embodiment of the electronic time delay circuit **212** is shown in FIG. **5**, various other circuit designs, including a time delay device and a voltage firing circuit are within the scope of the invention.

Returning to FIG. **3**, in one embodiment of the invention, output module **208** provides the detonation output to initiate the perforation gun **124** (see FIG. **2**). Output module **208** may comprise an output charge **250** and a prime charge **252**. By way of example only, explosive booster subassembly **208** may comprise 730 milligrams (mg) of hexanitrostilbene (HNS) output charge **250** and 200 mg of lead azide prime charge **252**. For example, and not limitation, the explosive booster subassembly **208** may be configured, upon detonation, to initiate subsequent explosive or propellant train events.

FIG. **6** is a flow diagram of an embodiment of a method of operation of electronic time delay assembly **126**. After a well perforation system is lowered down into a well and an oil or gas extraction process is ready to begin, as described above, an external force is applied **600** to the input module **206** located within a firing head. The external force acting on the firing pin of the input module **206** causes one or more shear pins to be sheared **602**, which enables the firing pin to displace within input module **206** and to connect a battery to the electronic time delay circuit. The electronic time delay circuit is then powered on and the desired time delay **604** is started. After the oscillator, in conjunction with the counter device, counts the time delay **606**, a fire command is issued to the gate of a high voltage generator transistor **608**. Subsequently, a first voltage, which is substantially higher than the battery voltage, is generated by transformer **610**. A voltage multiplier then generates a second voltage **612** which is substantially higher than the first intermediate voltage. The firing capacitors are then charged **614**, and upon reaching a firing voltage, a trigger device breaks down and an electrical pulse is applied to an initiator **616** which then initiates an explosive booster **618**.

Referring again to FIG. **2**, after the well **10** has been pressure balanced during the time delay and the perforating gun

124 has been fired, producing formation fluids under formation pressure will rapidly flow out of formation **120** into isolated zone **116** through vent **140** and upward through the tubing string **136** toward the earth's surface.

While embodiments of the electronic time delay apparatus of the present invention have been described and illustrated as having utility with a well perforating system, it is not so limited. For example, the electronic time delay apparatus of the present invention may be employed, in various embodiments, to initiate other explosive or propellant systems within a well bore, such as tubing or casing cutters. In addition, it is contemplated that embodiments of the electronic time delay apparatus of the present invention will find utility in subterranean mining and tunneling operations, in commercial, industrial and military demolition operations, in military ordnance, and otherwise, as will be readily apparent to those of ordinary skill in the relevant arts.

Specific embodiments have been shown by way of example in the drawings and have been described in detail herein; however, the invention may be susceptible to various modifications and alternative forms. It should be understood that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention includes all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the following appended claims.

What is claimed is:

1. A time delay apparatus, comprising:

an input assembly including an element configured to be displaced to enable a connection to a power source; and

an electronic time delay circuit operably coupled to the input assembly and comprising:

an electronic time delay device configured to provide a selectable, fixed time delay responsive to the connection to the power source and initiate a fire command upon completion of the selectable, fixed time delay, the electronic time delay device comprising:

a crystal oscillator with a frequency of 1 kHz or more;

a first counter device operably coupled to the crystal oscillator; and

a second counter device operably coupled to an output of the first counter device in a multiplier configuration;

wherein the first counter device and the second counter device can be programmed to provide the selectable, fixed time delay in a range of about eight minutes to multiple hours in increments of a clock cycle of the crystal oscillator;

a voltage firing circuit configured to increase a voltage provided by the power source to a trigger voltage; and

a trigger comprising a gas discharge tube configured to isolate the voltage firing circuit from an initiator until the trigger voltage is reached and convey the trigger voltage to the initiator when the voltage exceeds a predetermined threshold firing voltage.

2. The time delay apparatus of claim **1**, further comprising an output assembly including an explosive booster and configured to provide a detonation output responsive to the fire command.

3. The time delay apparatus of claim **1**, further comprising the power source coupled to the input assembly.

4. The time delay apparatus of claim **3**, wherein the input assembly comprises a contact assembly configured to engage the element upon displacement thereof and enable the power source connection.

5. The time delay apparatus of claim **3**, wherein the power source comprises a battery.

6. The time delay apparatus of claim **1**, wherein the element configured to be displaced comprises a firing pin, and the input assembly comprises a housing including a firing pin bore therein receiving the firing pin, and wherein the firing pin includes a longitudinal axis and is configured to be displaced along the longitudinal axis by an applied external force.

7. The time delay apparatus of claim **6**, further comprising at least one shear pin secured by the housing and extending substantially transversely through the firing pin, wherein the at least one shear pin is located and configured to be sheared by displacement of the firing pin responsive to the applied external force.

8. The time delay apparatus of claim **7**, wherein the at least one shear pin comprises a coiled spring pin.

9. The time delay apparatus of claim **3**, wherein the electronic time delay circuit is configured to bleed residual energy from the power source to a ground voltage after the time delay is completed.

10. The time delay apparatus of claim **1**, wherein the voltage firing circuit comprises at least one capacitor operably coupled to the trigger and configured to convey the increased voltage to the trigger.

11. The time delay apparatus of claim **1**, further comprising an explosive booster configured to provide a detonation output responsive to the fire command, wherein the initiator is configured to initiate the explosive booster upon receipt of the trigger voltage.

12. The time delay apparatus of claim **2**, wherein the explosive booster comprises substantially 730 mg of hexanitrostilbene (HNS) output charge.

13. The time delay apparatus of claim **2**, wherein the explosive booster comprises substantially 200 mg of lead azide prime charge.

14. The time delay apparatus of claim **2**, wherein the electronic time delay circuit is disposed within a substantially tubular housing.

15. The time delay apparatus of claim **14**, wherein the input assembly is secured to a first end of the substantially tubular housing.

16. The time delay apparatus of claim **14**, wherein the output assembly is secured to a second, opposing end of the substantially tubular housing.

17. A well perforation system, comprising:

a conveyance device;

a perforating gun suspended from the conveyance device;

a firing head suspended from the conveyance device and operably coupled to the perforating gun; and

a time delay apparatus within the firing head, comprising:

an input assembly including an element configured to be displaced to enable a connection to a power source; and

an electronic time delay circuit operably coupled to the input assembly and comprising:

an electronic time delay device configured to provide a selectable, fixed time delay responsive to the connection to the power source and initiate a fire command upon completion of the selectable, fixed time delay, the electronic time delay device comprising:

a crystal oscillator with a frequency of 1 kHz or more;

a first counter device operably coupled to the crystal oscillator; and

a second counter device operably coupled to an output of the first counter device in a multiplier configuration;

wherein the first counter device and the second counter device can be programmed to provide the selectable, fixed time delay in a range of about eight minutes to multiple hours in increments of a clock cycle of the crystal oscillator;

a voltage firing circuit configured to increase a voltage provided by the power source to a trigger voltage; and

a trigger comprising a gas discharge tube configured to isolate the voltage firing circuit from an initiator until the trigger voltage is reached and convey the trigger voltage to the initiator when the voltage exceeds a predetermined threshold firing voltage.

18. The well perforation system of claim **17**, wherein the time delay apparatus further comprises an output assembly including an explosive booster and configured to provide a detonation output responsive to the fire command.

19. The well perforation system of claim **17**, further comprising the power source coupled to the input assembly.

20. The well perforation system of claim **19**, wherein the input assembly comprises a contact assembly configured to engage the element upon displacement thereof and enable the power source connection.

21. The well perforation system of claim **19**, wherein the power source comprises a battery.

22. The well perforation system of claim **17**, wherein the element configured to be displaced comprises a firing pin, the input assembly comprises a housing including a firing pin bore therein receiving the firing pin, and wherein the firing pin includes a longitudinal axis and is configured to be displaced along the longitudinal axis by an applied external force.

23. The well perforation system of claim **22**, further comprising at least one shear pin secured by the housing and extending substantially transversely through the firing pin, wherein the at least one shear pin is located and configured to be sheared by displacement of the firing pin responsive to the applied external force.

24. The well perforation system of claim **23**, wherein the at least one shear pin comprises a coiled spring pin.

25. The well perforation system of claim **19**, wherein the electronic time delay circuit is configured to bleed residual energy from the power source to a ground voltage after the time delay is completed.

26. The well perforation system of claim **17**, wherein the voltage firing circuit comprises at least one capacitor operably coupled to the trigger and configured to convey the increased voltage to the trigger.

27. The well perforation system of claim **17**, further comprising an explosive booster configured to provide a detonation output responsive to the fire command, wherein the initiator is configured to initiate the explosive booster upon receipt of the trigger voltage.

28. The well perforation system of claim **18**, wherein the explosive booster comprises substantially 730 mg of hexanitrostilbene (HNS) output charge.

29. The well perforation system of claim **18**, wherein the explosive booster comprises substantially 200 mg of lead azide prime charge.

30. The well perforation system of claim **18**, wherein the electronic time delay circuit is disposed within a substantially tubular housing.

31. The well perforation system of claim **30**, wherein the input assembly is secured to a first end of the substantially tubular housing.

32. The well perforation system of claim **31**, wherein the output assembly is secured to a second, opposing end of the substantially tubular housing.

33. A time delay apparatus, comprising:

an input assembly including an element configured to be displaced and contact each of a first contact assembly and a second contact assembly to enable a connection to a power source; and

an electronic time delay circuit operably coupled to the input assembly and comprising:

an electronic time delay device configured to provide a fixed time delay responsive to the connection to the power source and initiate a fire command upon completion of the fixed time delay, the electronic time delay device comprising:

a crystal oscillator with a frequency of 1 kHz or more;

a first counter device operably coupled to the crystal oscillator; and

a second counter device operably coupled to an output of the first counter device in a multiplier configuration;

wherein the first counter device and the second counter device can be programmed to provide the fixed time delay in a range of about eight minutes to multiple hours in increments of a clock cycle of the crystal oscillator;

a voltage firing circuit configured to increase a voltage provided by the power source to a trigger voltage; and

a trigger comprising a gas discharge tube configured to isolate the voltage firing circuit from an initiator until the trigger voltage is reached and convey the trigger voltage to the initiator when the voltage exceeds a predetermined threshold firing voltage.

34. A well perforation system, comprising:

a conveyance device;

a perforating gun suspended from the conveyance device;

a firing head suspended from the conveyance device and operably coupled to the perforating gun; and

a time delay apparatus within the firing head, comprising:

an input assembly including an element configured to be displaced to enable a connection to a power source;

an electronic time delay circuit operably coupled to the input assembly and comprising:

an electronic time delay device configured to provide a fixed time delay responsive to the connection to the power source and initiate a fire command upon completion of the fixed time delay, the electronic time delay device comprising:

a crystal oscillator with a frequency of 1 kHz or more;

a first counter device operably coupled to the crystal oscillator; and

a second counter device operably coupled to an output of the first counter device in a multiplier configuration;

wherein the first counter device and the second counter device can be programmed to provide the fixed time delay in a range of about eight minutes to multiple hours in increments of a clock cycle of the crystal oscillator;

a voltage firing circuit configured to increase a voltage provided by the power source to a trigger voltage; and

a trigger comprising a gas discharge tube configured to isolate the voltage firing circuit from an initiator until the trigger voltage is reached and convey the trigger voltage to the initiator when the voltage exceeds a predetermined threshold firing voltage; and

an output assembly adjacent the electronic time delay circuit and configured to provide a detonation output.

35. A time delay apparatus, comprising:

an input assembly including an element configured to be displaced to enable a connection to a power source; and

an electronic time delay circuit operably coupled to the input assembly and comprising:

an electronic time delay device configured to provide a fixed time delay responsive to the connection to the power source and initiate a fire command upon completion of the fixed time delay, wherein the time delay circuit includes:

a crystal oscillator configured to oscillate with a frequency of 1 kHz or more after initiation of the fire command to bleed residual energy from the power source;

a first counter device operably coupled to the crystal oscillator; and

a second counter device operably coupled to an output of the first counter device in a multiplier configuration;

wherein the first counter device and the second counter device can be programmed to provide the fixed time delay in a range of about eight minutes to multiple hours in increments of a clock cycle of the crystal oscillator;

a voltage firing circuit configured to increase a voltage provided by the power source to a trigger voltage; and

a trigger comprising a gas discharge tube configured to isolate the voltage firing circuit from an initiator until the trigger voltage is reached and convey the trigger voltage to the initiator when the voltage exceeds a predetermined threshold firing voltage.

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